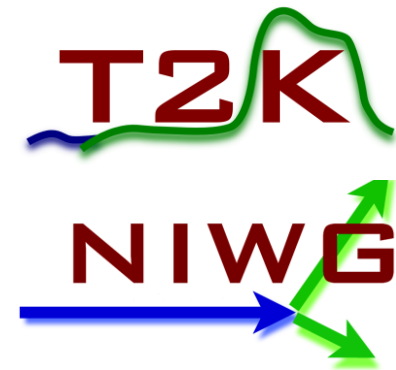


T2K Cross-Section Model for Oscillation Analyses

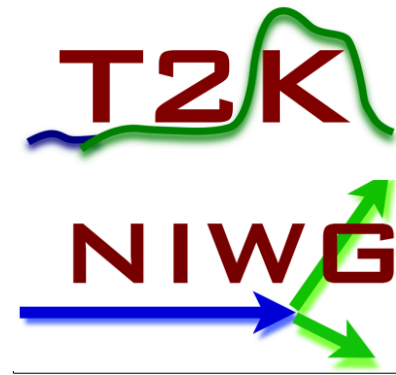
*T2K jargon for
“Neutrino Interactions
Working Group”,
pronounced “noog”*

FNAL ND Seminar
Kevin McFarland
University of Rochester
6 April 2017

Goals for Today's Talk



- Remind you of T2K and its oscillation analysis
- Explain the components of the interaction model, and along the way...
 - What is chosen and why?
 - What are the weaknesses and areas of development
 - How is new data being used?
 - What are the next steps
- I hope some of this will be useful for your oscillation experiment's work



T2K OSCILLATION ANALYSES

T2K Detectors and Observables

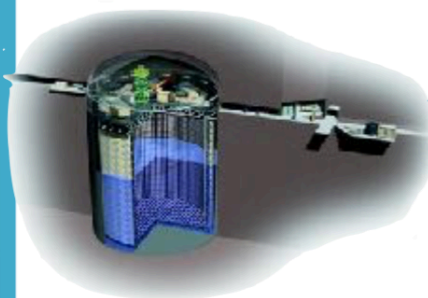
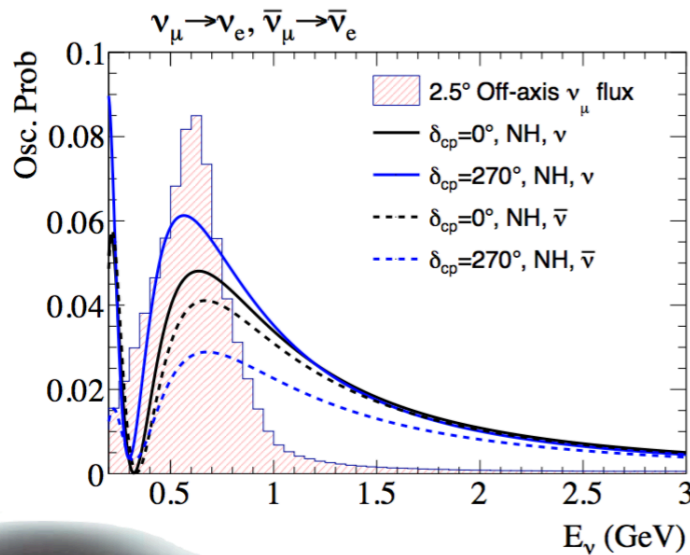
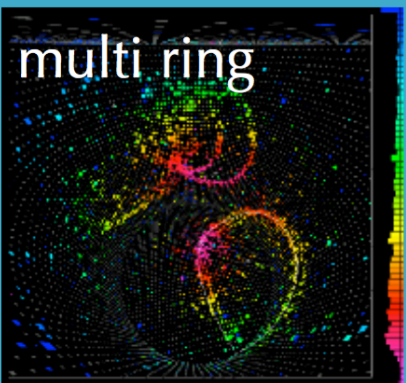
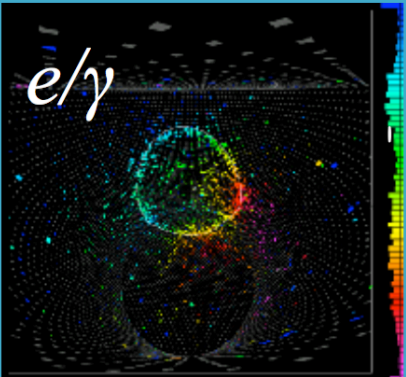
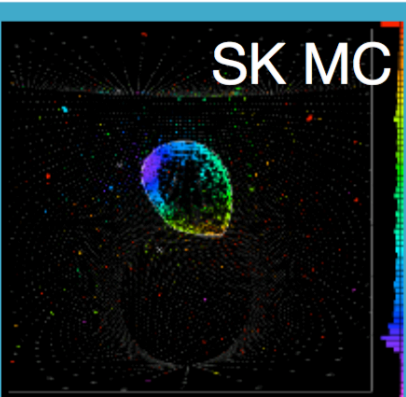
Near Detector Constraint

Where we are today

T2K in One Picture

T2K
NIWG

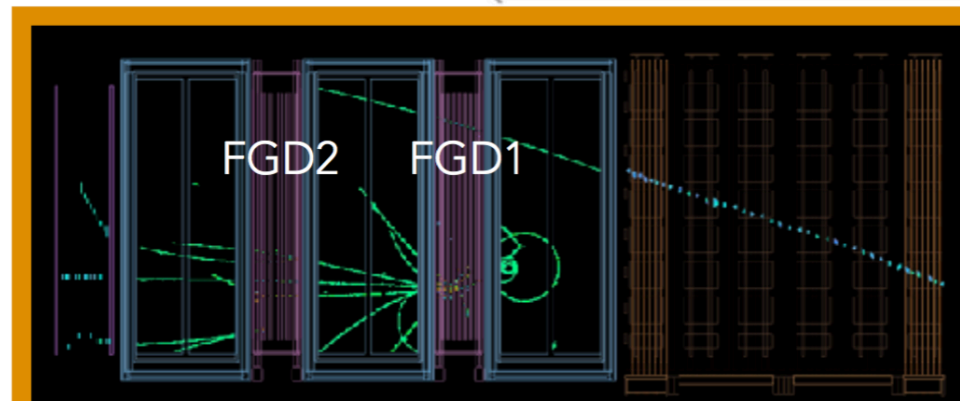
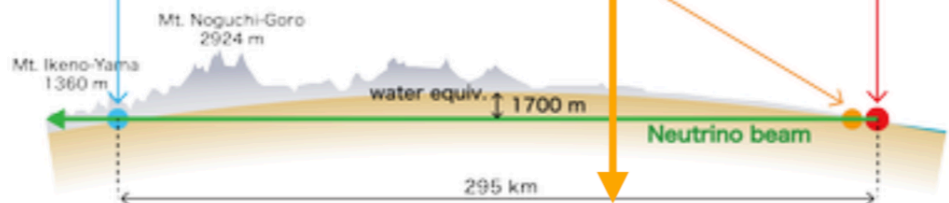
Graphic
by Hiro
Tanaka



Super Kamiokande

Near Detector

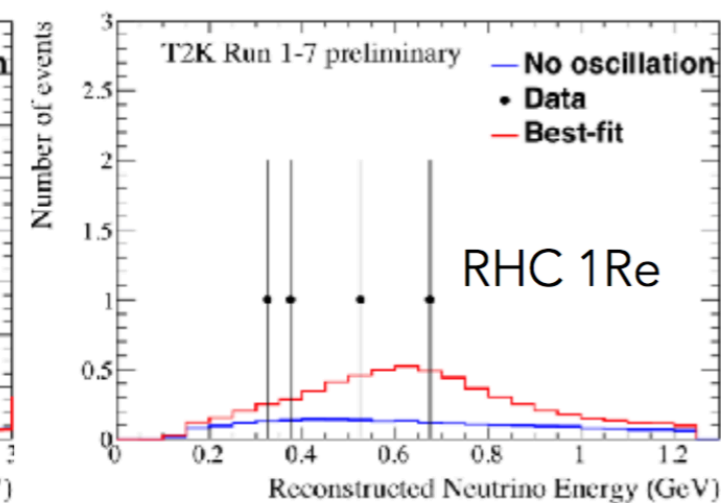
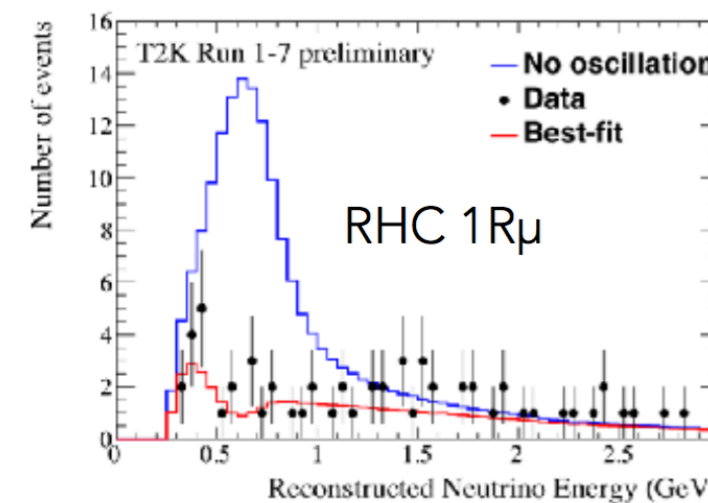
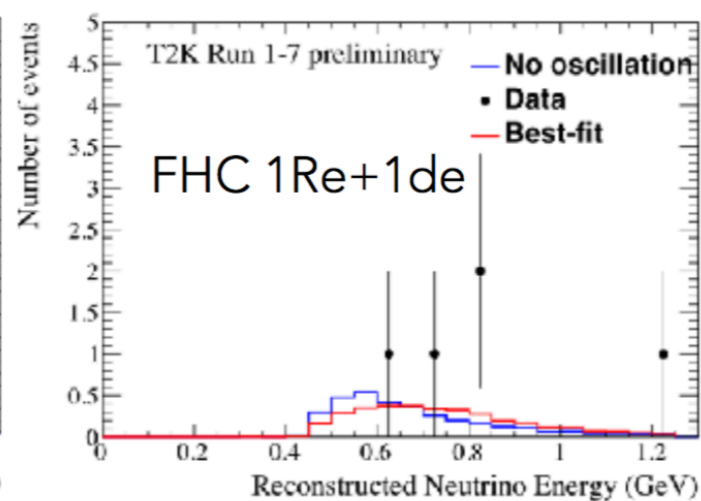
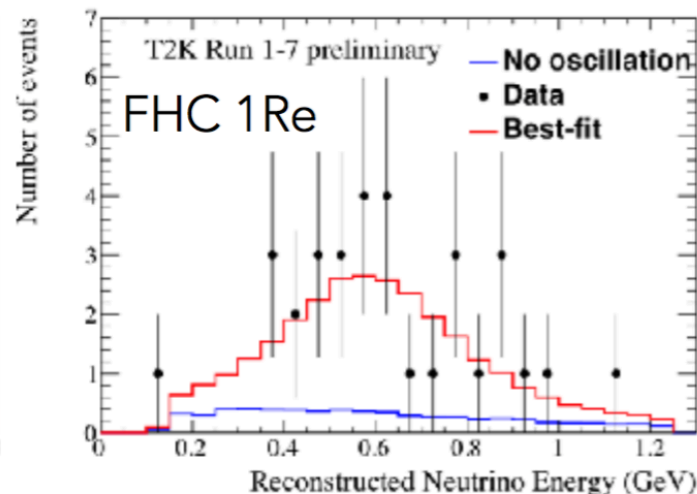
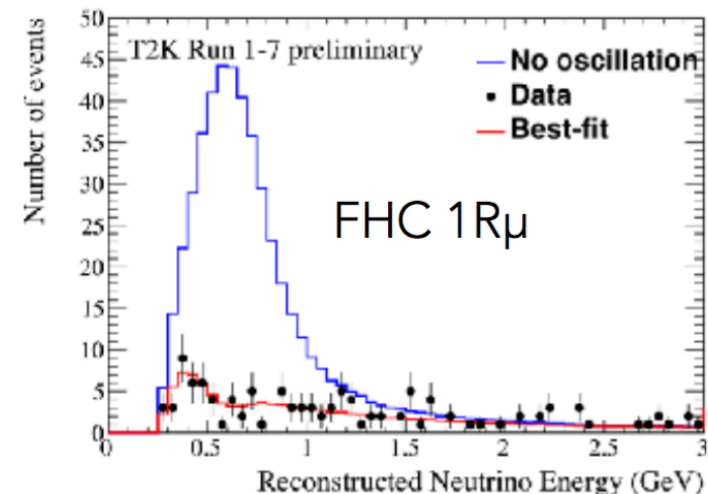
J-PARC



6 April
2017

T2K Cross-
Section Model

Events at Far Detector



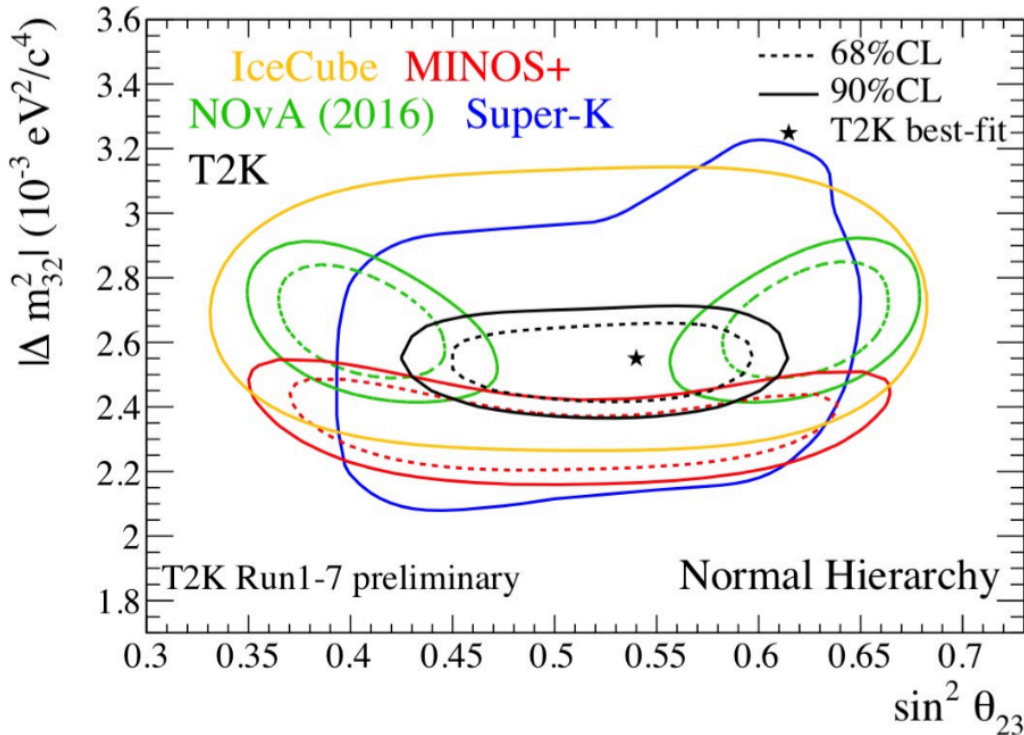
Events: No Osc→Obs

| | FHC | RHC |
|----------|---------|--------|
| 1Re | 6→32 | 2.4→4 |
| 1Re+de | 0.8→5 | n/a |
| 1R μ | 481→135 | 177→66 |

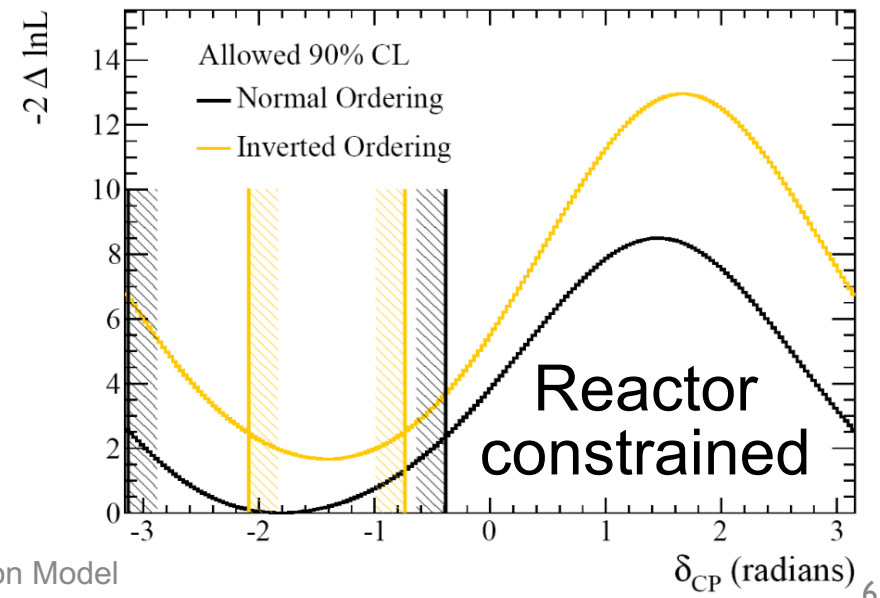
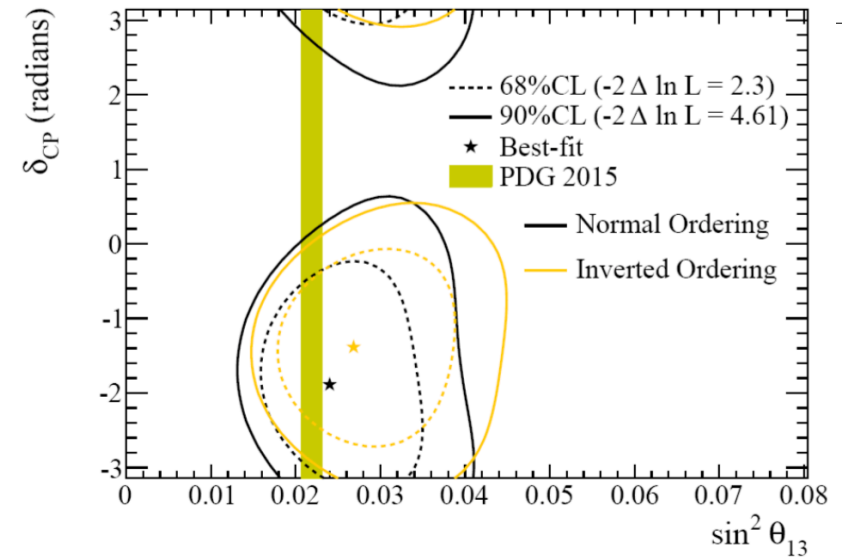
New sample: CC1 π^+ (1Re+1de)
Decay electron from $\pi \rightarrow \mu \rightarrow e$

Oscillation Parameters

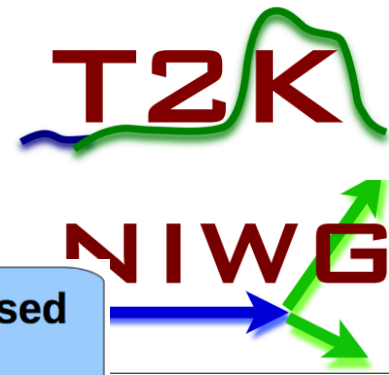
T2K
NIWG



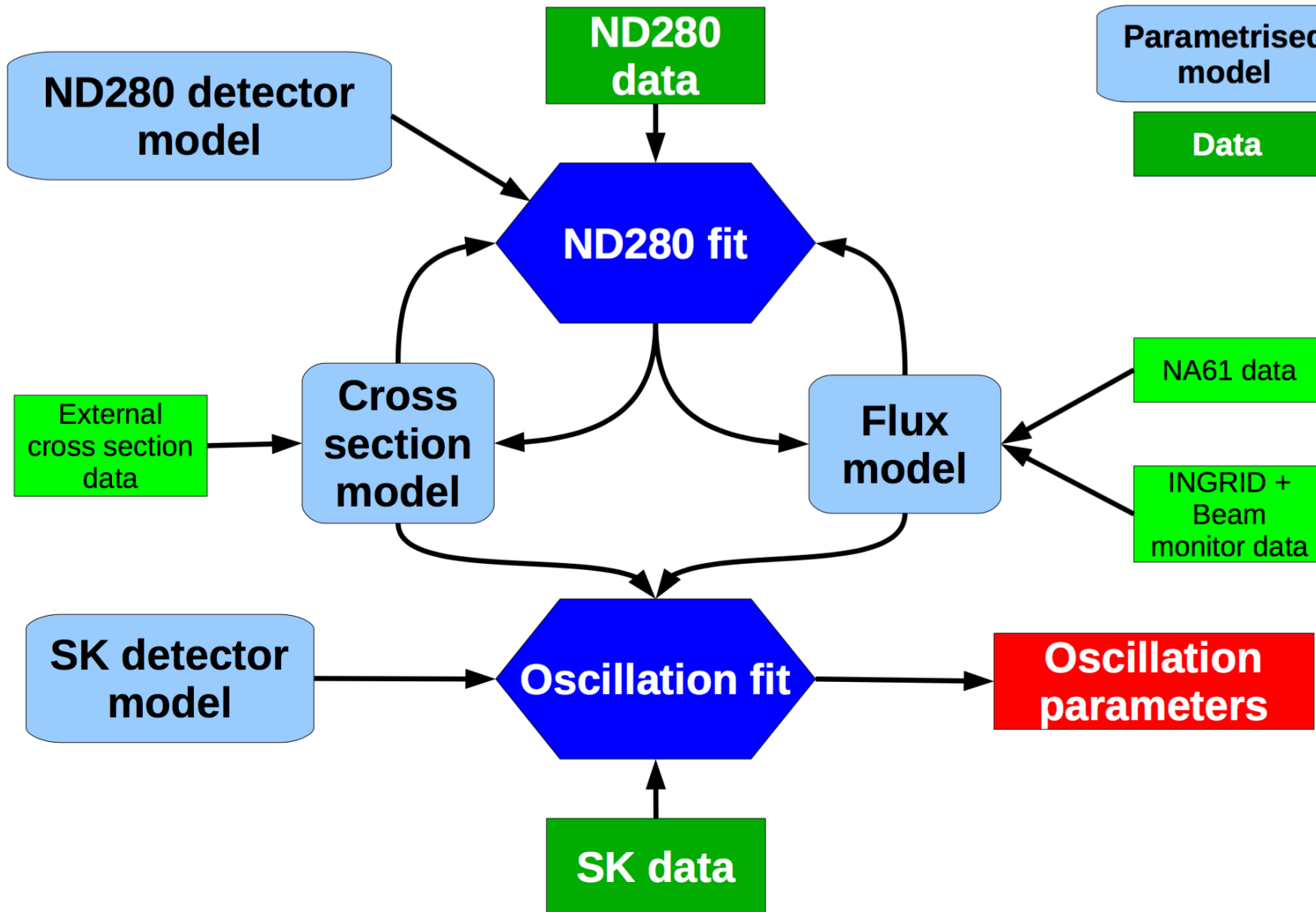
- Large ν_μ disappearance suggests maximal mixing
- Large ν_e appearance suggests normal ordering, 2nd octant and $\delta_{CP} \sim -\pi/2$



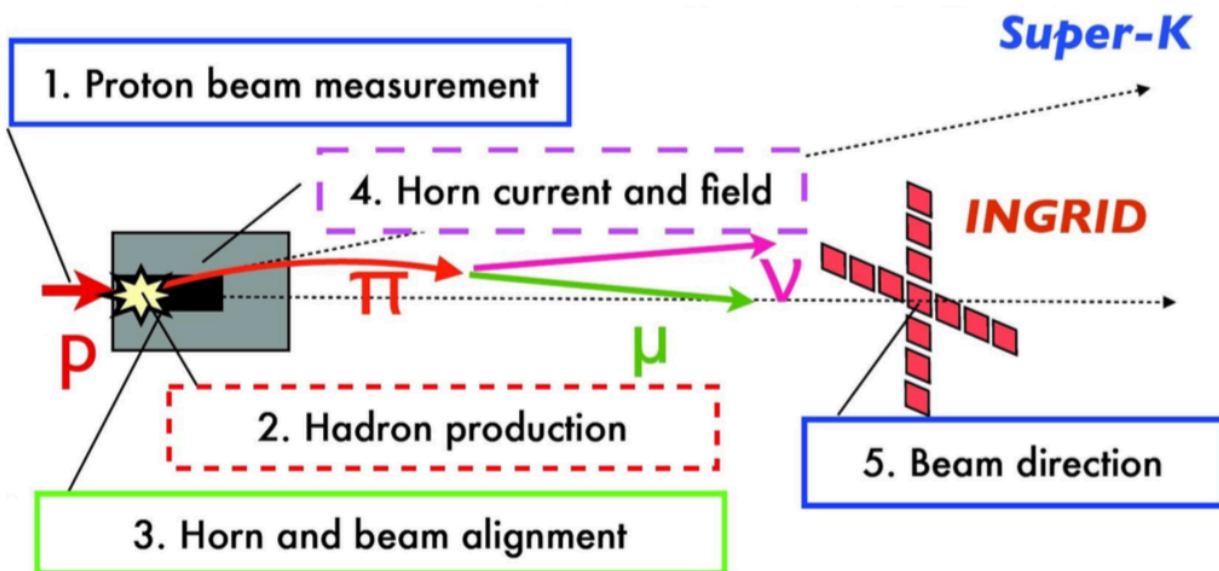
Schematic of Osc. Analysis



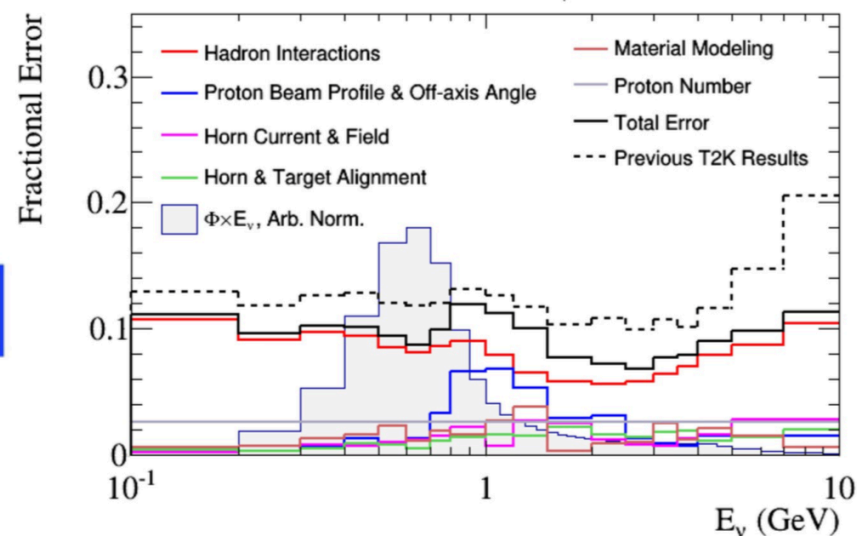
Graphic
by Mark
Scott



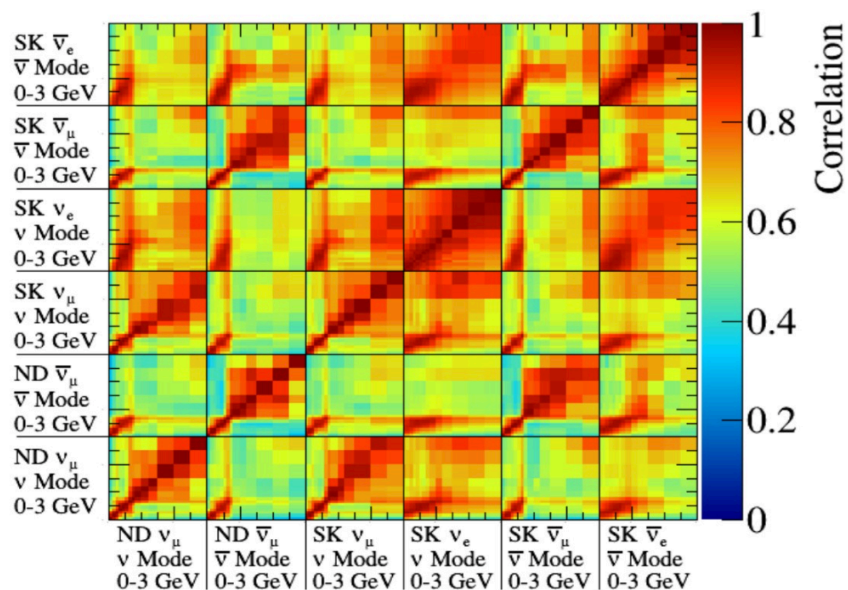
Flux Prediction



ND280: Positive Focussing Mode, ν_μ



Flux Correlations

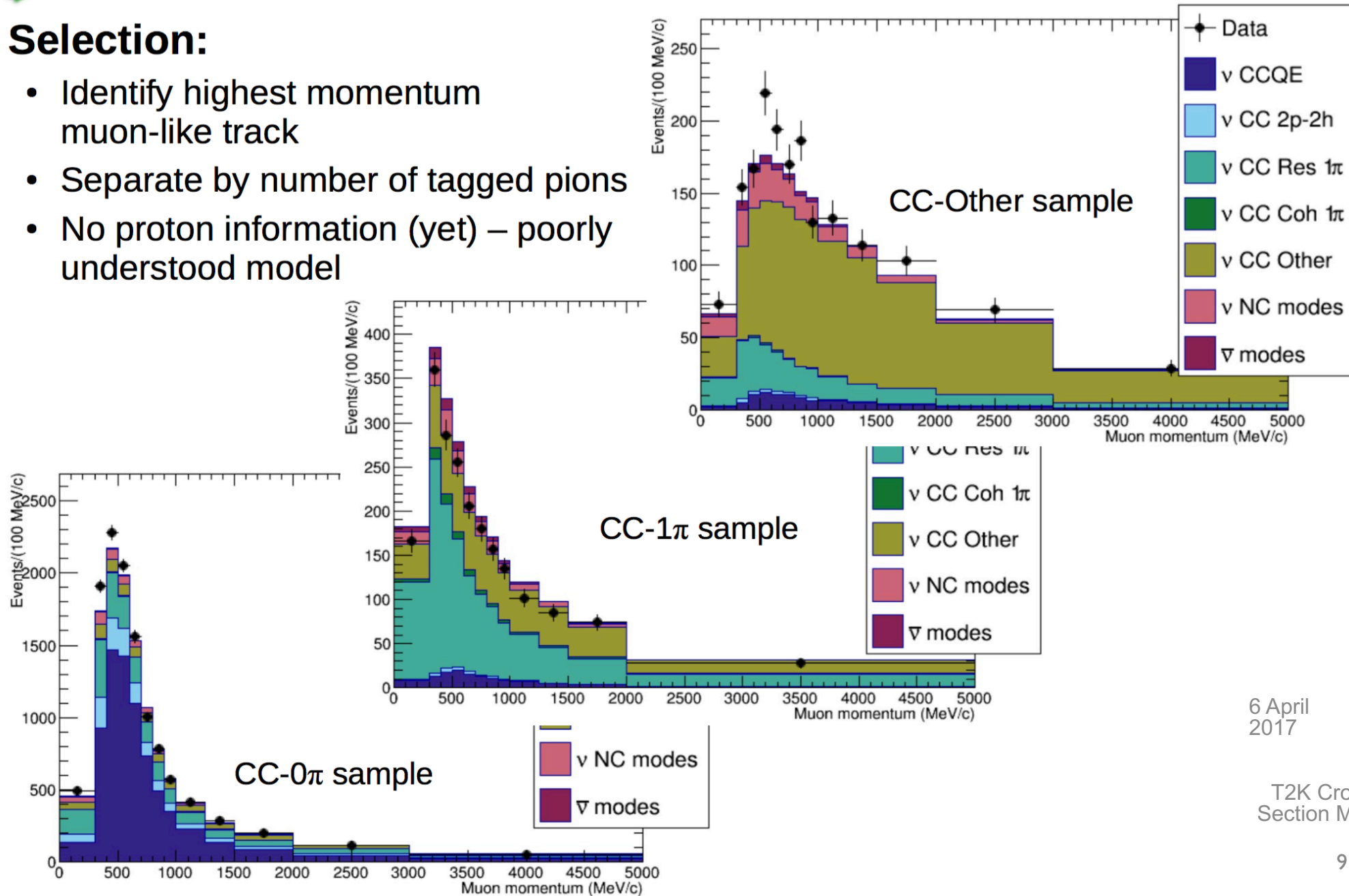


- Driven by hadroproduction data
- Correlates near & far detector flux and different flavors
- Expect significant reduction soon from replica target data

Near Detector Samples

Selection:

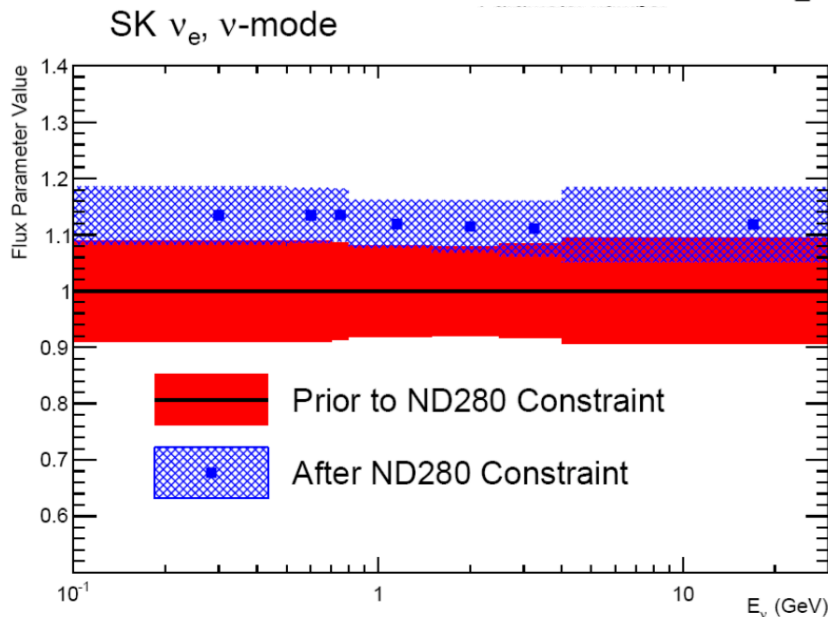
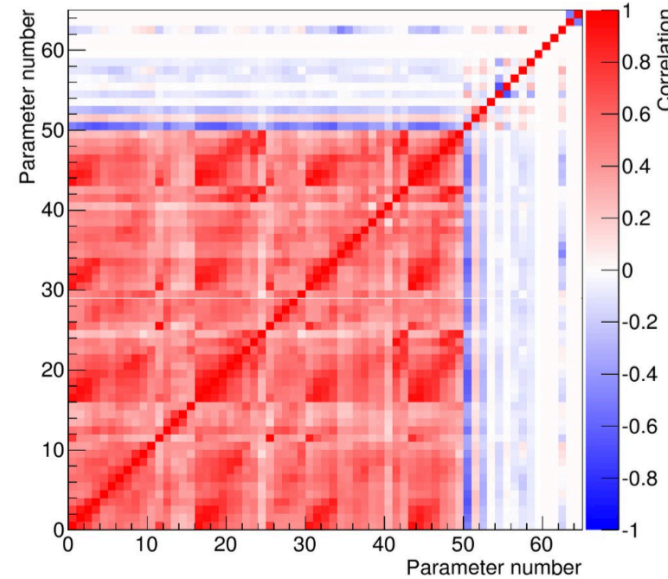
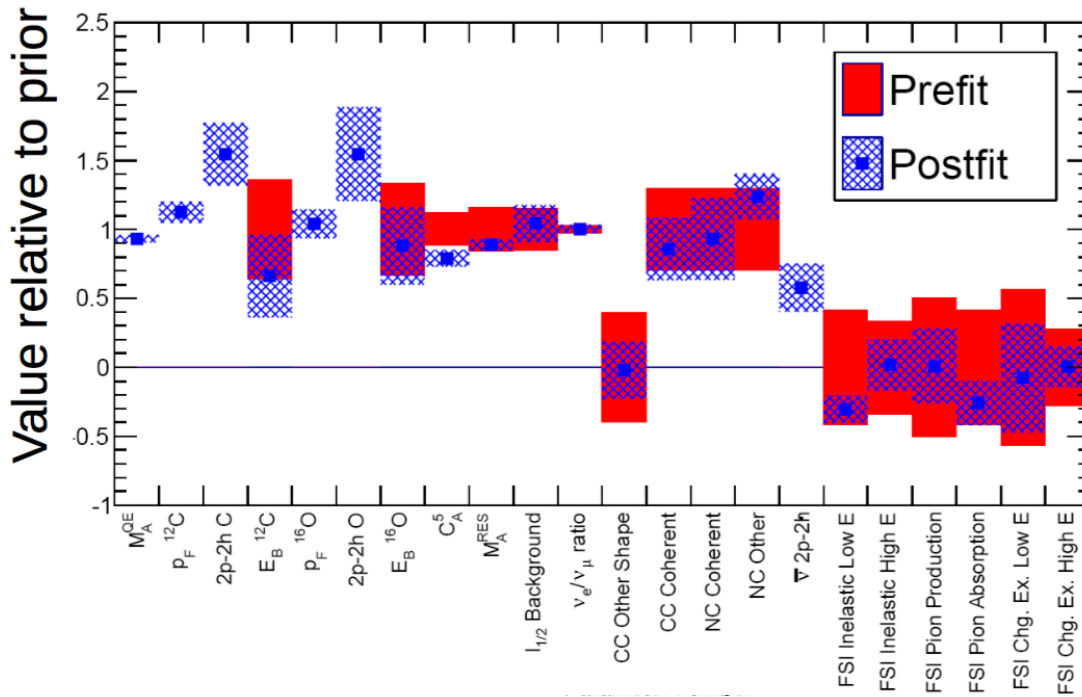
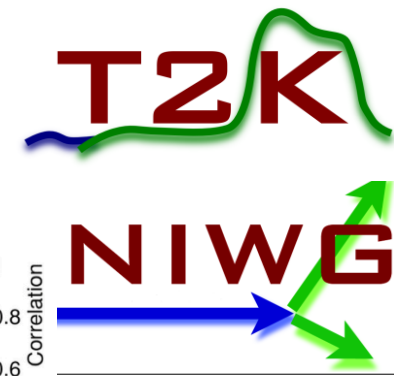
- Identify highest momentum muon-like track
- Separate by number of tagged pions
- No proton information (yet) – poorly understood model



6 April
2017

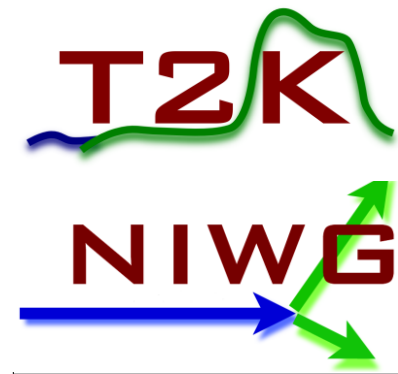
T2K Cross-
Section Model

Result of ND Constraint



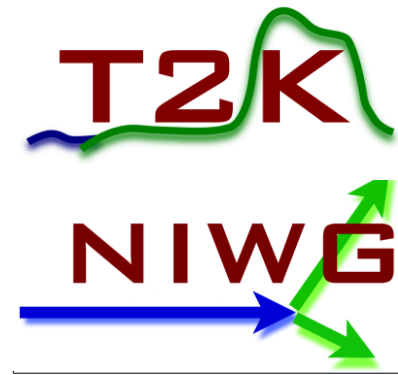
- Flux and cross section become anticorrelated, with reduced uncertainties
- Parameters of the flux and cross section model that propagate information from near to far detector

Illustration of Constraint



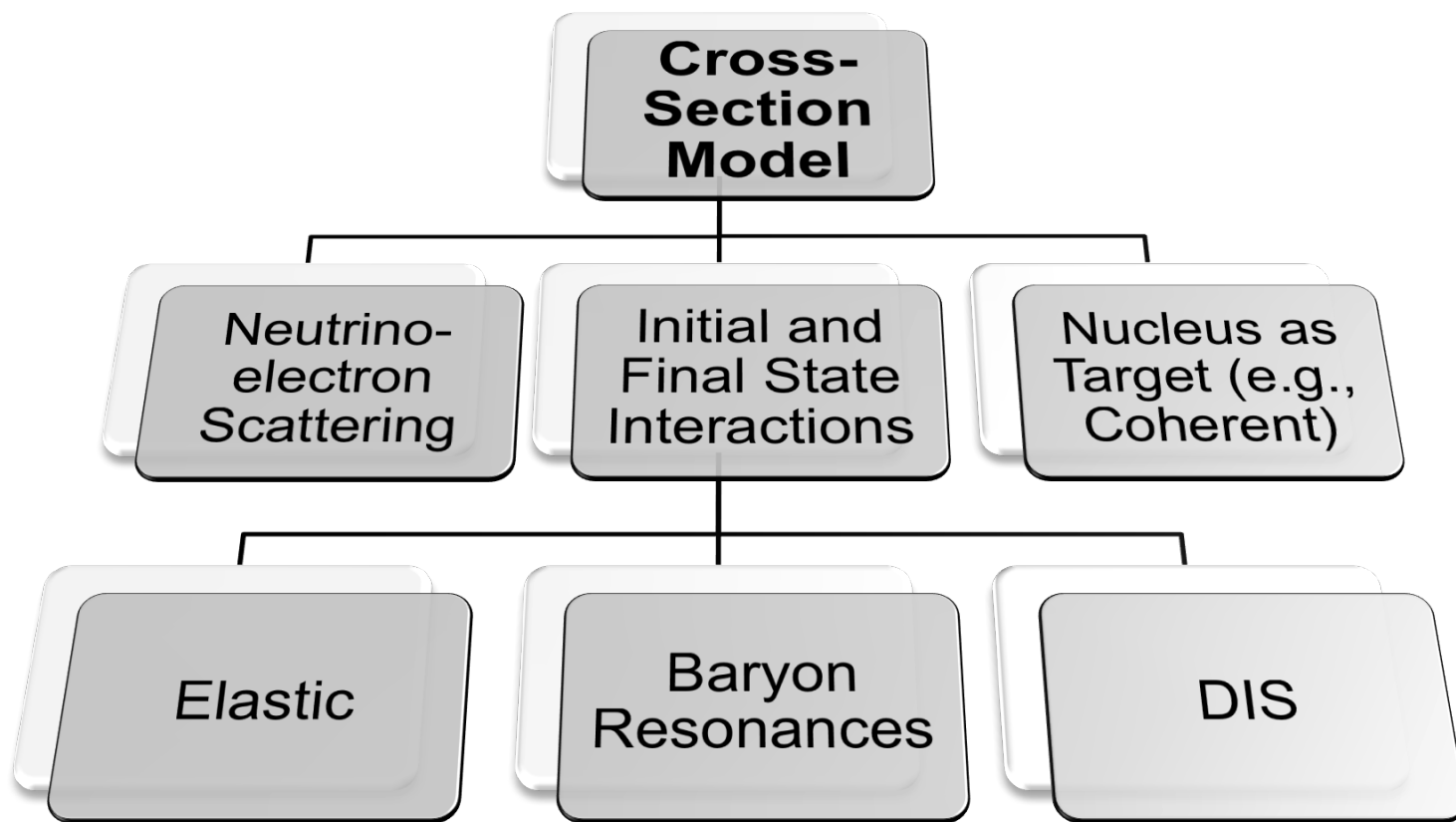
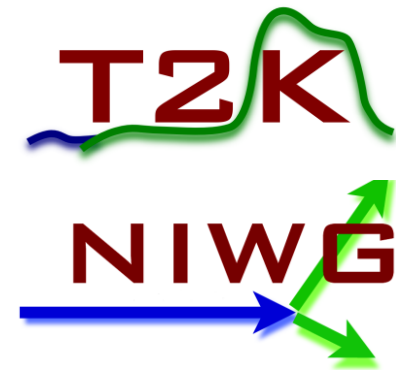
- What happens to systematic uncertainties with near detector constraint?

| FHC ν_e CC0 π | Pre- ND Fit | | | Post- ND Fit | | |
|-------------------------------|-------------|-----------|------|--------------|-----------|-----|
| Sample | mean | 1σ | % | mean | 1σ | % |
| Flux | 24.24 | 2.13 | 8.8 | 26.50 | 0.95 | 3.6 |
| Xsec | 24.38 | 1.72 | 7.0 | 26.92 | 1.38 | 5.1 |
| Flux+Xsec | 24.41 | 2.79 | 11.4 | 26.78 | 1.09 | 4.1 |
| Flux+Xsec (constrained by ND) | 24.26 | 2.63 | 10.9 | 26.63 | 0.77 | 2.9 |
| SK+FSI+SI | 24.35 | 0.89 | 3.7 | 26.70 | 0.96 | 3.6 |
| All | 24.48 | 2.96 | 12.1 | 26.85 | 1.47 | 5.5 |



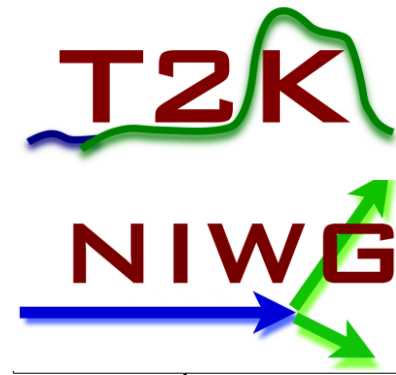
OVERVIEW OF CROSS-SECTION MODEL

Architecture of Model



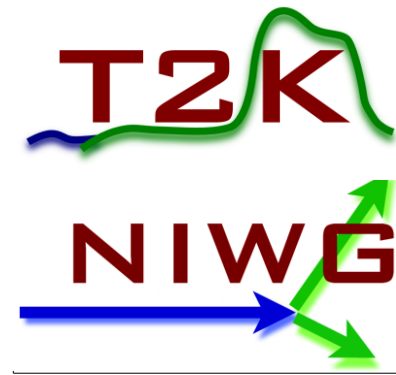
Nucleus
(including
C vs O)

Nucleon



Is the architecture sound?

- Models of these components are inadequate
 - E.g., “Final State Interactions” as a semi-classical model of transport of on-shell hadrons
 - Can’t even rigorously factorize problem!
- Data constraints are essential for selecting models and measuring parameters
 - But some data is missing, or ambiguous
 - Models may not fit data, or may be missing components, so it is easy to build in the model assumption somewhere to the downselection



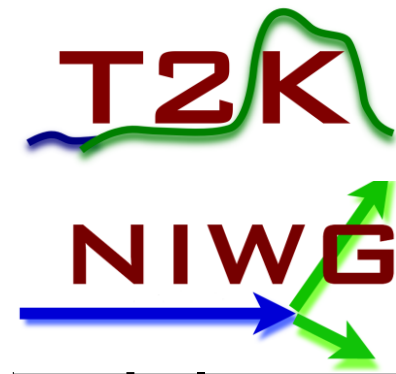
NUCLEON COMPONENTS

Nucleon: Elastic, Baryon Resonance, DIS

Nuclear Modifications: Initial State, 2p2h, Screening (RPA), FSI

Processes on Nucleus: Neutrino-electron scattering, Coherent

Elastic Processes on Nucleons



- Recall: nuclear effects not in nucleon model

- So Llewellyn Smith, as one does C.H. Llewellyn Smith,
Phys. Rep. 3C, 261 (1972)

$$\frac{d\sigma}{dQ^2}(\nu n \rightarrow l^- p) = \left[A(Q^2) \mp B(Q^2) \frac{s-u}{M^2} + C(Q^2) \frac{(s-u)^2}{M^4} \right] \times \frac{M^2 G_F^2 \cos^2 \theta_c}{8\pi E_\nu^2}$$

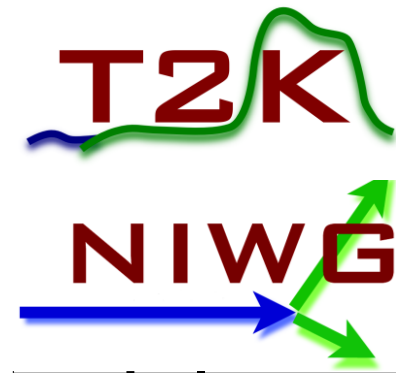
$$A(Q^2) = \frac{m^2 + Q^2}{4M^2} \left[\left(4 + \frac{Q^2}{M^2} \right) |F_A|^2 - \left(4 - \frac{Q^2}{M^2} \right) |F_V^1|^2 + \frac{Q^2}{M^2} \xi |F_V^2|^2 \left(1 - \frac{Q^2}{4M^2} \right) + \frac{4Q^2 \text{Re} F_V^{1*} \xi F_V^2}{M^2} - \frac{Q^2}{M^2} \left(4 + \frac{Q^2}{M^2} \right) |F_A^3|^2 - \frac{m^2}{M^2} \left(|F_V^1 + \xi F_V^2|^2 + |F_A + 2F_P|^2 - \left(4 + \frac{Q^2}{M^2} \right) (|F_V^3|^2 + |F_P|^2) \right) \right],$$

$$B(Q^2) = \frac{Q^2}{M^2} \text{Re} F_A^* (F_V^1 + \xi F_V^2) - \frac{m^2}{M^2} \text{Re} \left[\left(F_V^1 - \frac{Q^2}{4M^2} \xi F_V^2 \right)^* F_V^3 - \left(F_A - \frac{Q^2 F_P}{2M^2} \right)^* F_A^3 \right] \text{ and}$$

$$C(Q^2) = \frac{1}{4} \left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{M^2} \left| \frac{\xi F_V^2}{2} \right|^2 + \frac{Q^2}{M^2} |F_A^3|^2 \right).$$

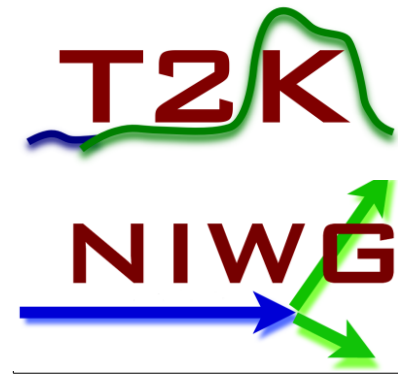
Occupants of the form factor zoo:
 F_V^1, F_V^2 are vector form factors;
 F_A is the axial vector form factor;
 F_P is the pseudo-scalar form factor;
 F_V^3 and F_A^3 are form factors related to currents requiring G-parity violation, small?

Elastic Processes on Nucleons (cont'd)



- Recall: nuclear effects not in nucleon model
- Llewellyn-Smith, as one does
 - BBBA07 vector form factors
 - Axial Form factor from deuterium CCQE, pion electroproduction
 - Assume Goldberger–Treiman, $F_P = \mathcal{F}(F_A)$
 - Dipole in current publications, but moving to z-expansion or ad hoc three component models (correct high Q^2 uncertainty)
- Photon emission in CC radiative corrections

Elastic Processes on Nucleons (cont'd)



- Several additional poorly constrained uncertainties

M. Day and K. S. McFarland.
Phys. Rev. D 86, 053003 (2012)

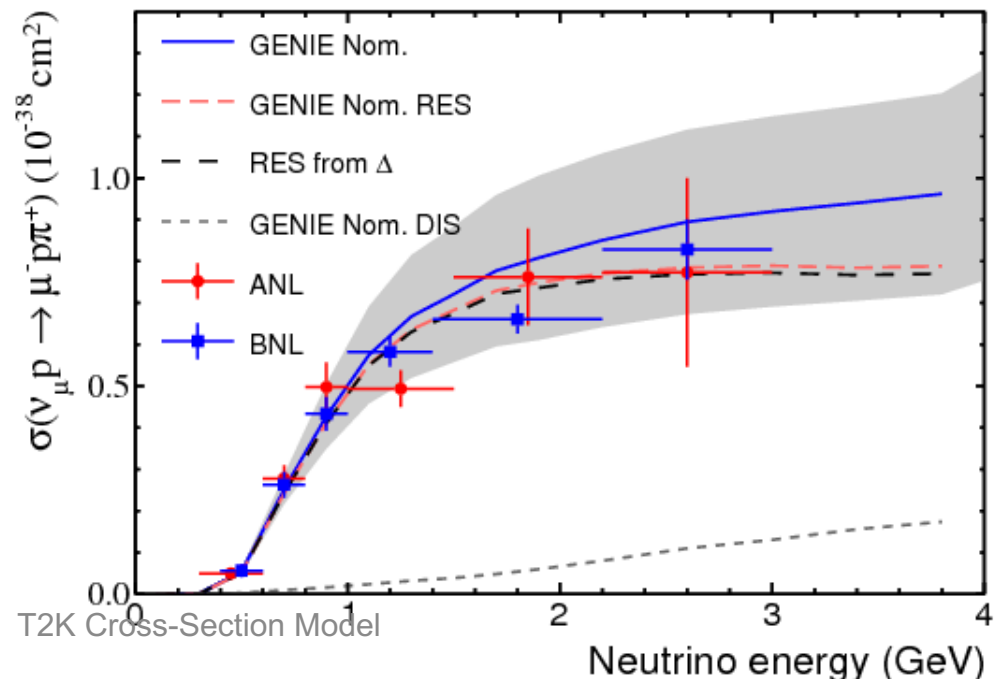
- Possibility of nuclear induced second class current effective form factors
 - At T2K energies, $\sim 2\%$ difference in ν_e and ν_μ CC elastic cross sections possible. Less at high energy
- At all energies, EWK vertex corrections differences for ν_e and ν_μ thought to be “small” (KNL theorem), but there is no calculation
 - T2K puts in an additional 2% systematic
- Lumped together as a ν_e/ν_μ uncertainty

Baryon Resonance Model

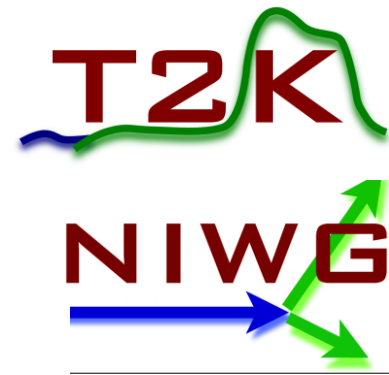
- Rein-Sehgal, with its dramatic deficiencies
 - Many unknown axial couplings and form factors, lumped into a dipole axial form factor, C_A^5 , m_A^{RES}
 - Ad hoc non-resonant “background” model also tuned to deuterium data (after ANL/BNL “fix”)

P. Rodrigues, C. Wilkinson
and K. McFarland, Eur. Phys.
J. C 76, 474 (2016)

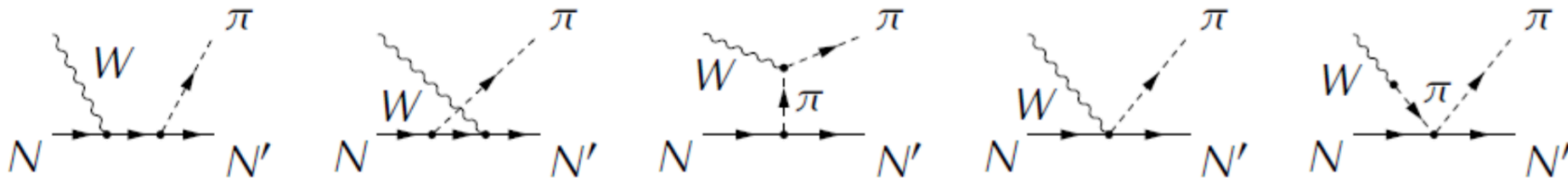
C. Wilkinson et al, Phys. Rev.
D 90, no. 11, 112017 (2014)



Pion Model Improvement

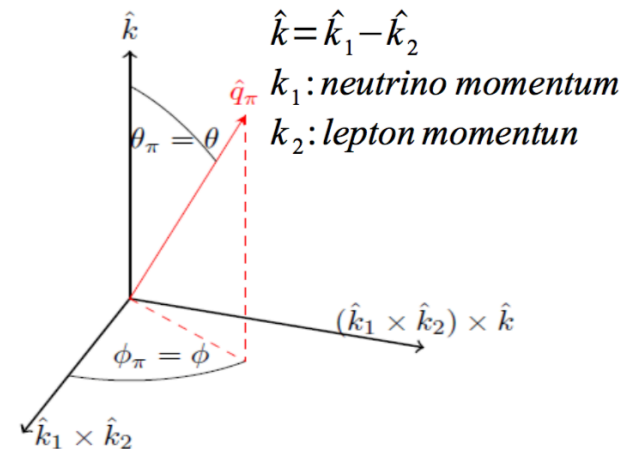


- The new model covers all pions from resonant (Rein-Sehgal model) and non-resonant interactions (5 diagrams from Hernandez et.al) coherently!



E. Hernandez, J. Nieves and M. Valverde,
Phys. Rev. D 76 (2007) 033005

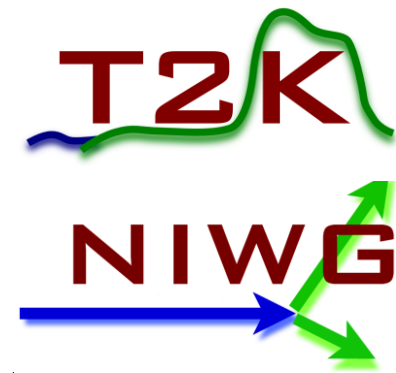
- Lepton mass is included and It is suitable for MC
We need to define a common framework to calculate the helicity amplitudes. Isobaric system
- The main challenge is to calculate helicity amplitudes of the above diagrams in this frame
- The new model output is $d\sigma/dW dQ^2 d\Omega_\pi$
pion angles are part of cross-section!



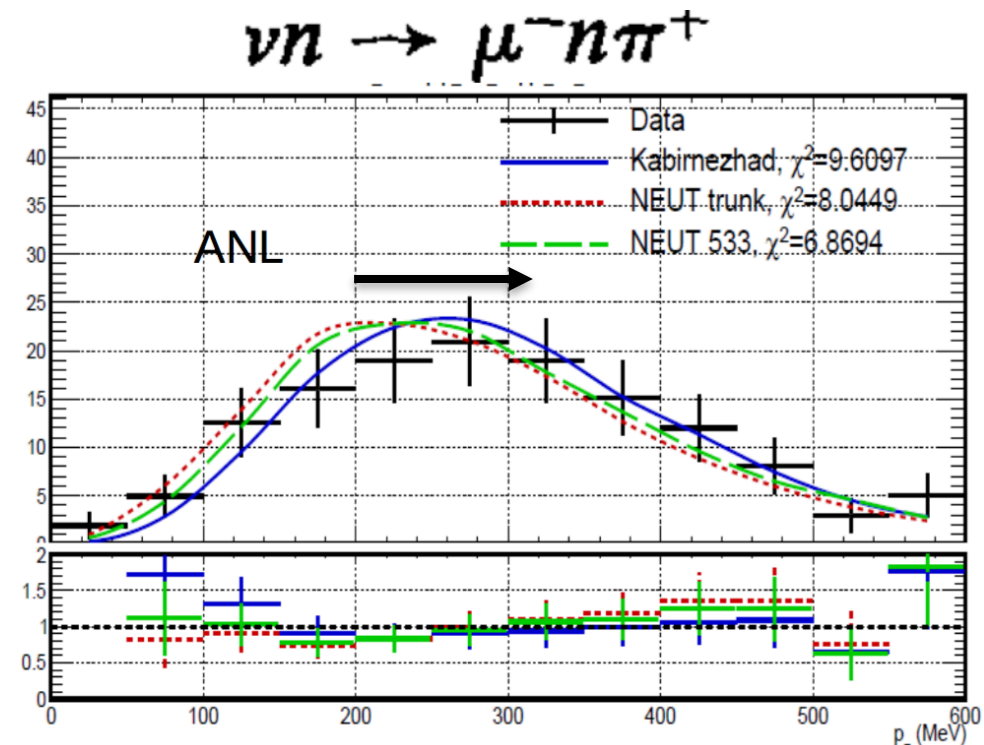
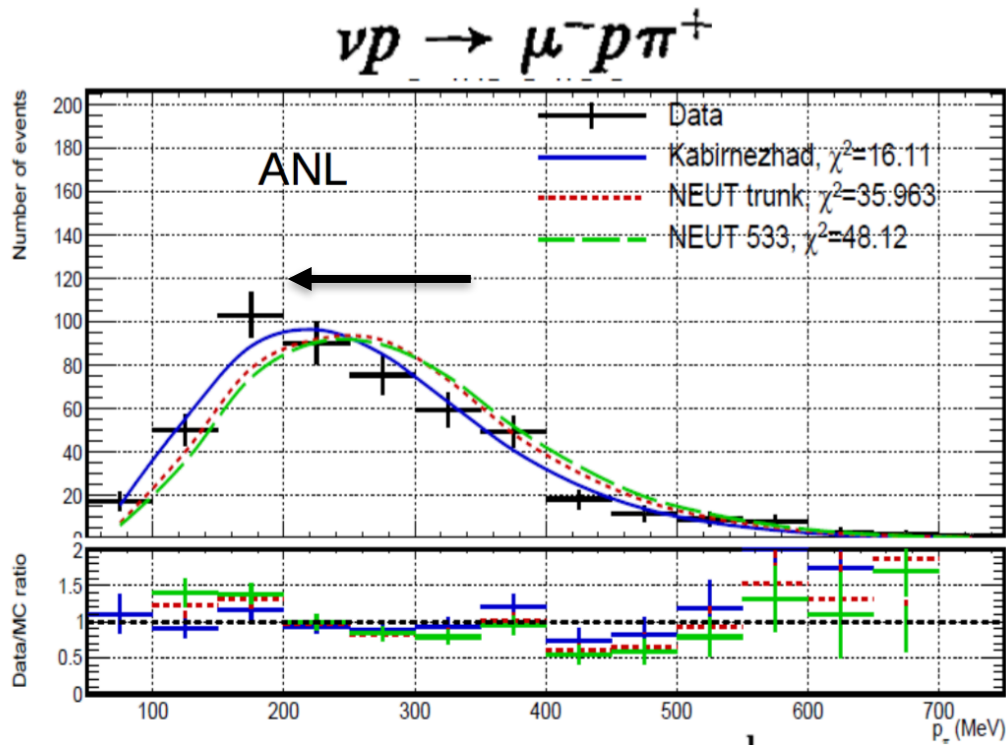
Work by
Minoo
Kabirnezhad

- Interference between resonant and non-resonant makes tuned Rein-Sehgal predictive in different channels!

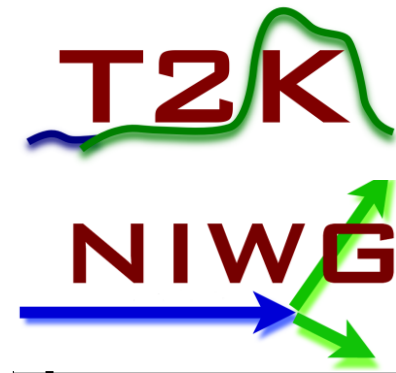
Pion Model Improvement



Work by
Minoo
Kabirnezhad



- Difference in the W spectrum because of interference shifts the pion momentum spectrum. Note improvement!

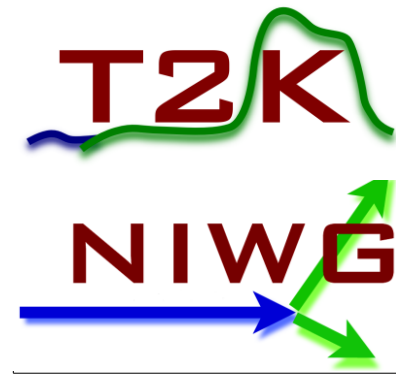


Baryon Resonance Model

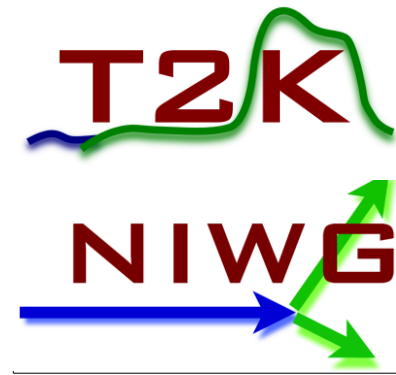
- Rein-Sehgal, with its dramatic deficiencies
 - Many unknown axial couplings and form factors, lumped into a dipole axial form factor, C_A^5 , m_A^{RES}
 - Ad hoc non-resonant “background” model also tuned to deuterium data (after ANL/BNL “fix”)
- Single pion events only; multipion at low W is taken from DIS model
- $\text{NC}1\gamma$ from Alvarez-Ruso, scaled to Wang et al study, 100% uncertainty

E. Wang et al, Phys. Rev.,
D92, 053005 (2015)

DIS



- Not very significant at T2K energy, and accordingly, not as sophisticated as GENIE
- Use above W of 2 GeV
- Free-nucleon PDFs in LO model. Bodek-Yang extension to low Q^2 form factor
- Fragmentation from PYTHIA
- $W < 2$ GeV multipion fragmentation handled separately and tuned on hydrogen data (custom tune)



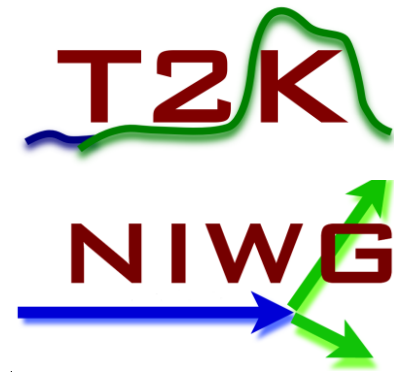
NUCLEAR COMPONENTS

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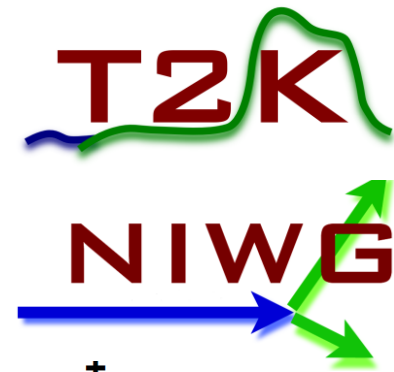
Processes on Nucleus: Neutrino-electron scattering, Coherent

Neutrino-Electron Scattering

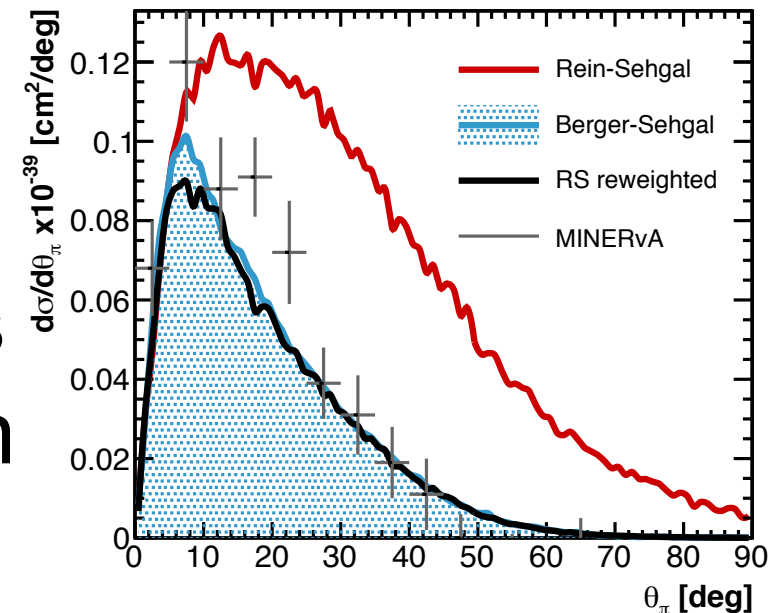
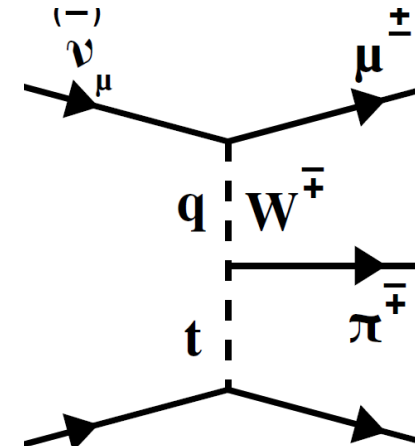


- Textbook prediction. Can be used as a standard candle to measure neutrino flux.
- Like in GENIE (hint), no careful selection of $\sin^2\theta_W$ and no treatment of radiative corrections
 - In fact, the right calculation of radiative corrections for NOvA, DUNE, MINERvA has not been done yet because $E_e \neq E_\nu^{initial} - E_\nu^{final}$
- T2K is not using this method currently

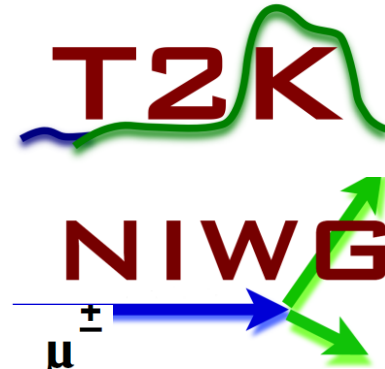
Coherent/Diffractive Pion Production



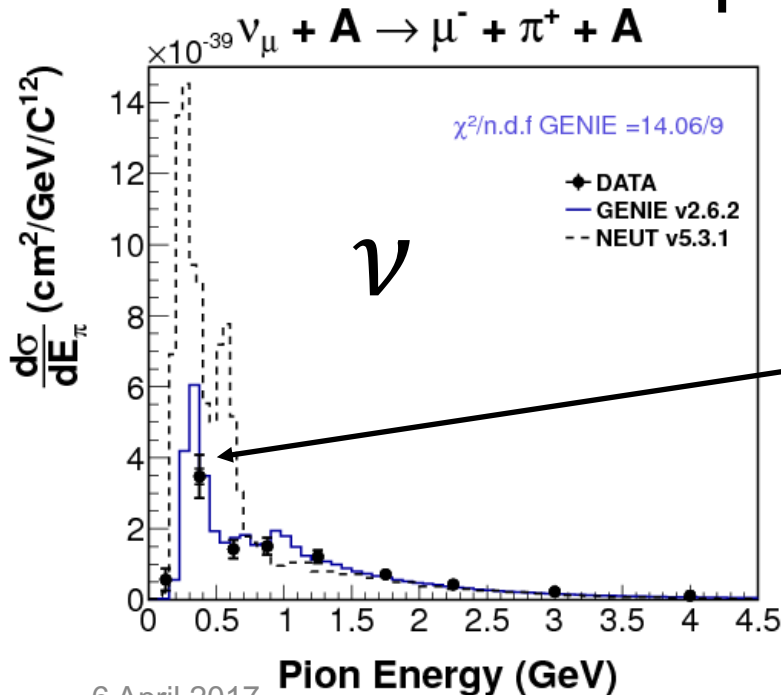
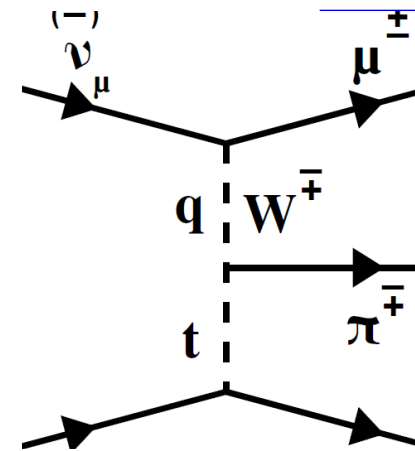
- Previous NEUT implementation of Rein-Sehgal had original π C elastic scattering cross-section
 - GENIE default has improved one based on new data
- Recently implemented Berger-Sehgal because of its good agreement with modern (MINERvA) data



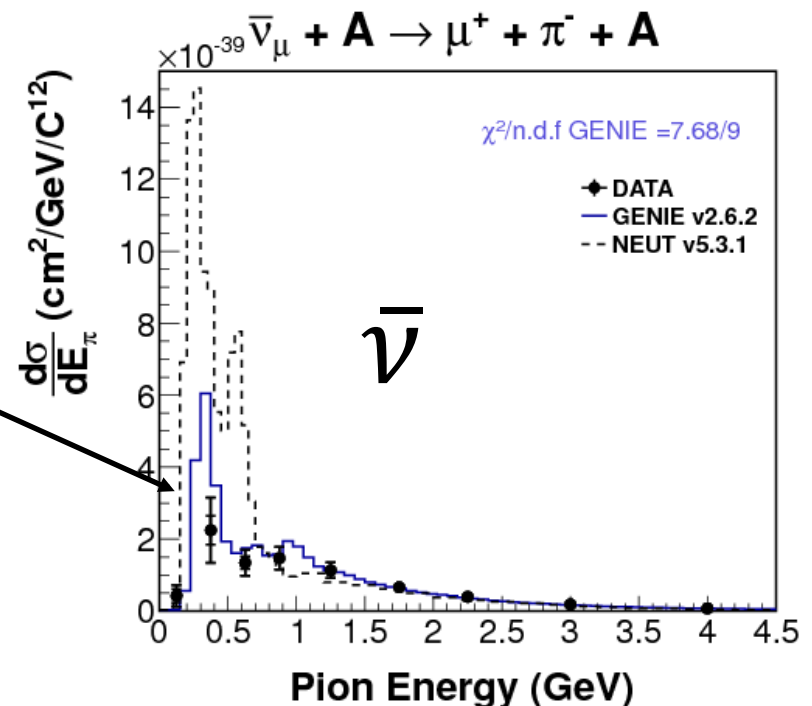
Coherent/Diffractive Pion Production (cont'd)



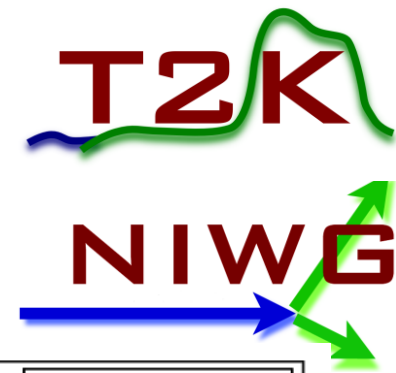
- GENIE implementation of Rein-Sehgal coherent model is better than NEUT's
- But... still not perfect



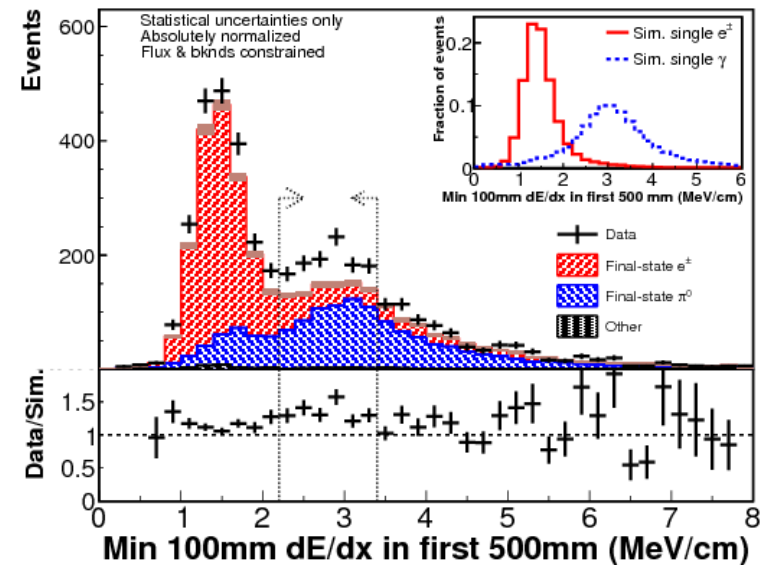
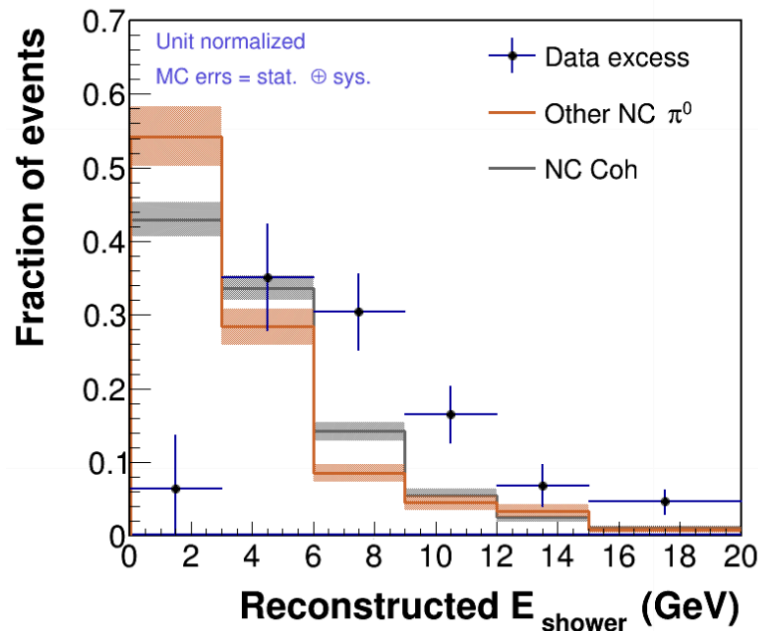
GENIE low pion energy is not so great. Matters most at low energy.



Coherent/Diffractive Pion Production (cont'd)



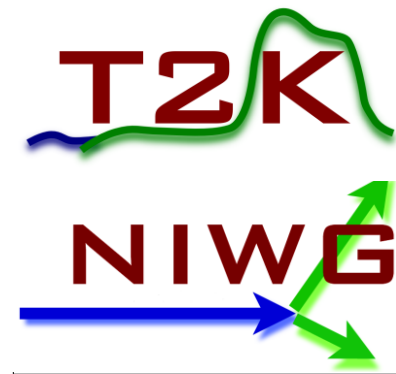
- MINERvA also observed a “diffractive like” process as a background to its ν_e CC0 π
- Hard spectrum inconsistent with resonant or coherent scattering



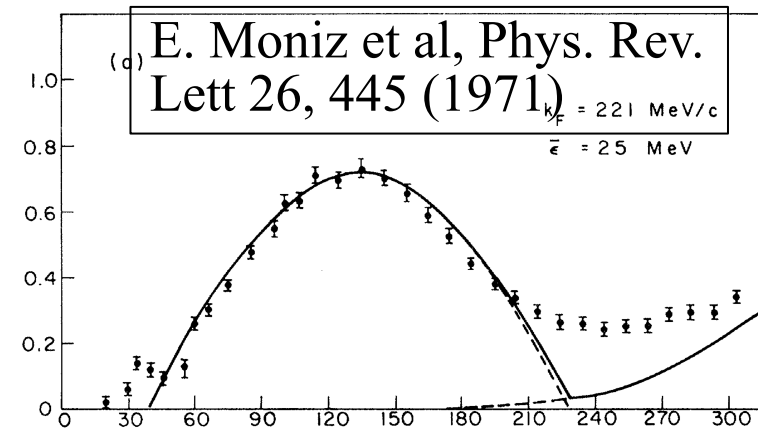
J. Wolcott et al Phys.Rev.Lett.
117 (2016) no.11, 111801

- Rein model common to GENIE, NEUT, has ~right spectrum, but rate is too low
- Likely unimportant for T2K

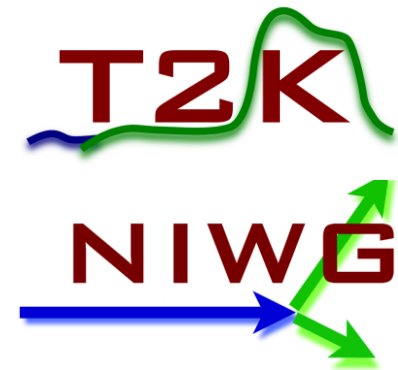
Initial State Model



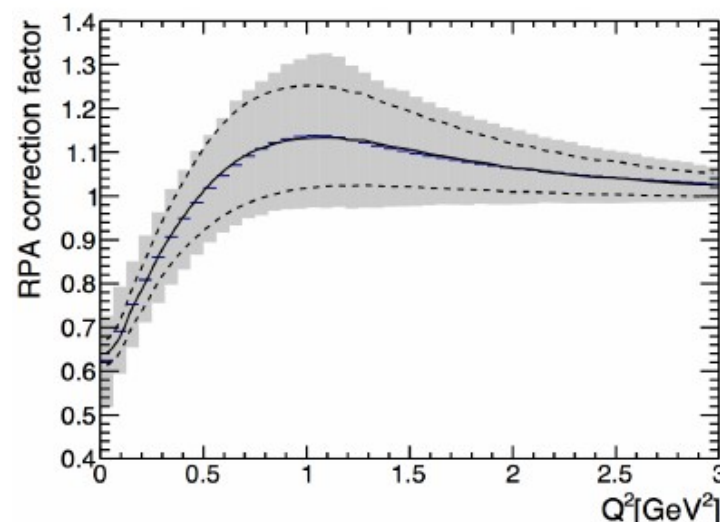
- Use a Fermi Gas model with binding (E_B) and Fermi momentum (k_F) parameters
 - e^- corrected to neutrino data
 - C/O differences included
- Many worries here
 - Not all parts of model use same IS
 - Corrections are uncertain, and uncertainties matter
 - Not valid when we go to a new IS model
- Alternate IS models available now or soon
 - Local Fermi Gas, Spectral function (Benhar), Effective SF (Bodek et al), etc.

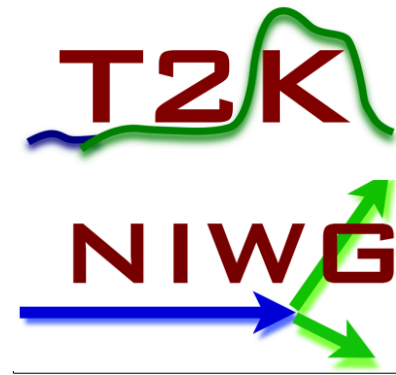


Nuclear Screening (RPA)



- Long-range nucleon-nucleon correlations screen low momentum transfer reactions
 - Random Phase Approximation or “RPA”
- Use calculation of Nieves et al
 - MINERvA, MiniBooNE data support it
- Have evaluated uncertainties in calculation
 - Current oscillation analysis is still using m_A variations as a proxy for this
 - “Effective RPA” model, constrained by theory
- Only known for elastic nucleon processes, although data says needed in pion production





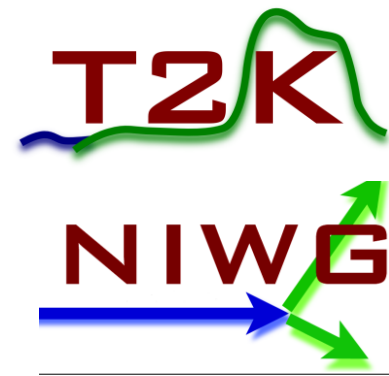
2p2h processes

- I want to avoid writing a novel here, although I certainly could do that if desired
- Evidence from MINERvA, MiniBooNE and electron scattering that this process exists
- We use an *ab initio* calculation from Nieves et al, same one that is in GENIE. But...
 - It is not complete.
 - Different (also incomplete) calculations get very different strengths and q_0 vs q_3 distributions
 - Differences matter for T2K. A lot.

J. Nieves et al., Phys. Rev. C83:045501, 2011.

M. Martini et al., Phys. Rev., C80:065501, 2009.

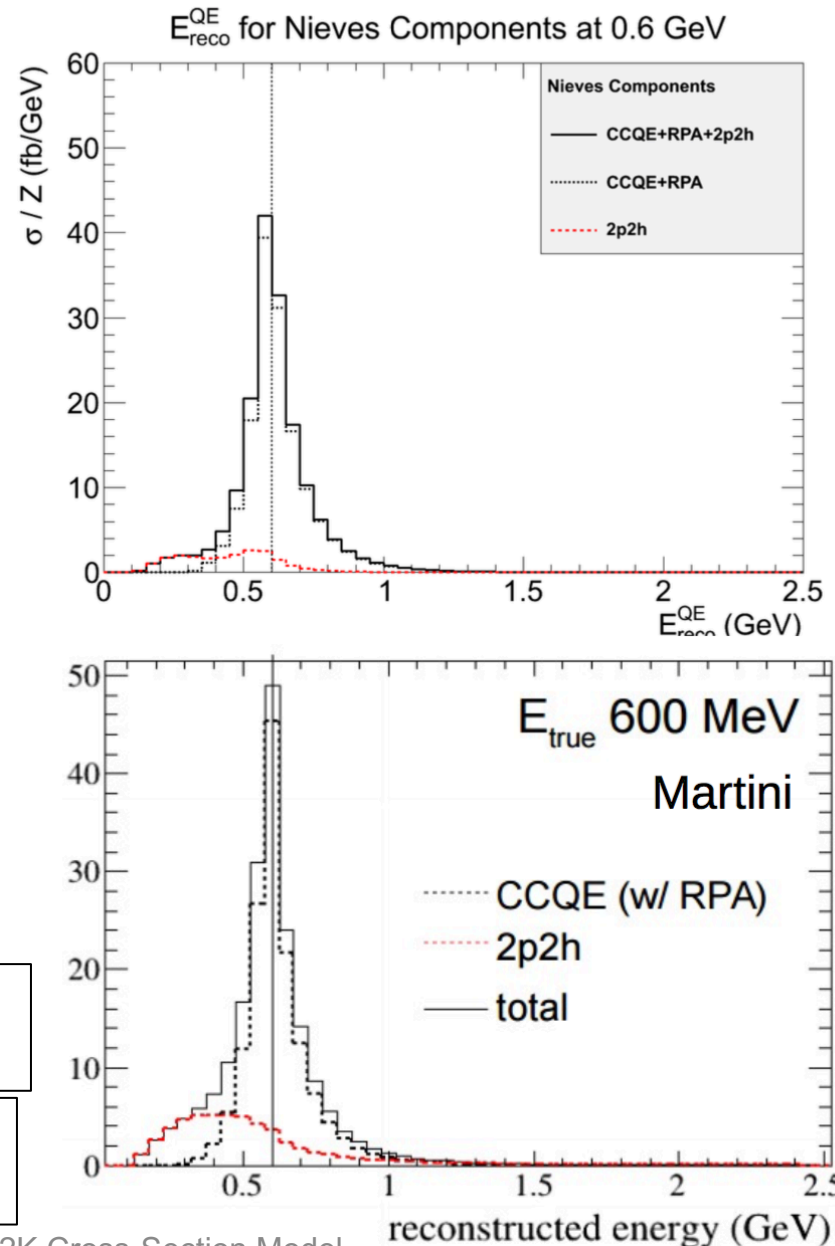
2p2h processes (cont'd)



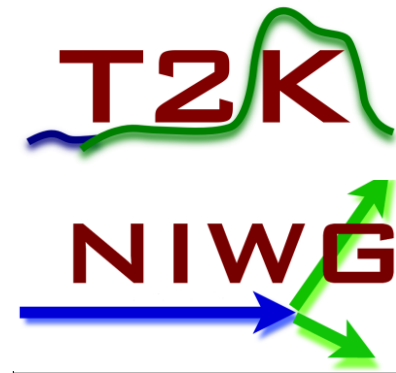
- Especially in disappearance analysis, need a reliable neutrino energy estimator
- The difference in incomplete calculations lead to different reconstructed energy

J. Nieves et al., Phys. Rev. C83:045501, 2011.

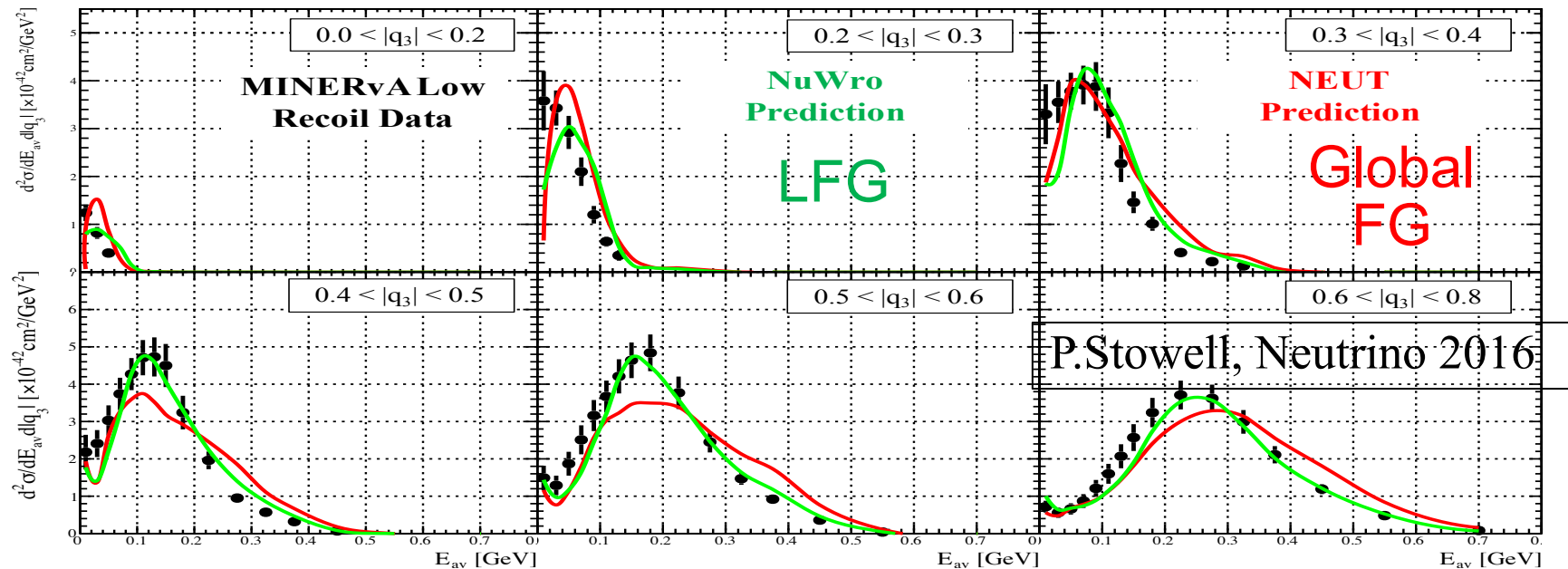
M. Martini et al., Phys. Rev., C80:065501, 2009.

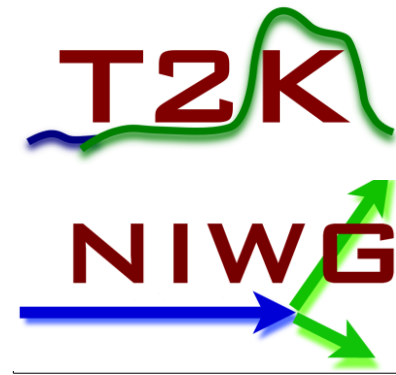


2p2h processes (cont'd)



- Not easy to constrain from data
 - Models not generally benchmarked against electron scattering. (Not a panacea, but it would help.)
 - Data on CCQE rate vs Q^2 has many uncertainties (e.g., IS, RPA, form factors), so hard to pin down 2p2h
- MINERvA low recoil also subject to variations in 1p1h



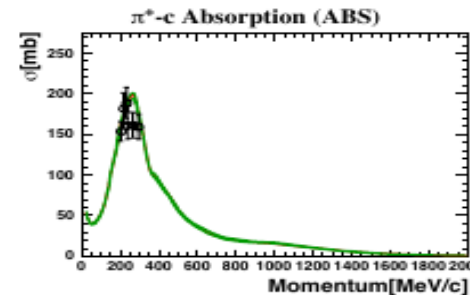
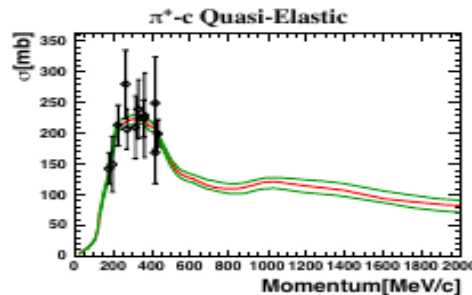
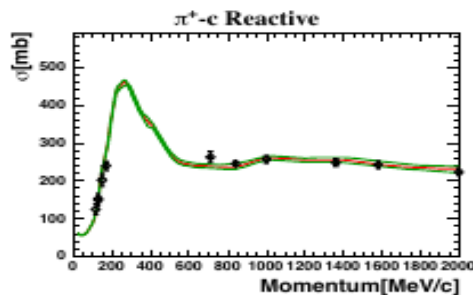


2p2h processes (cont'd)

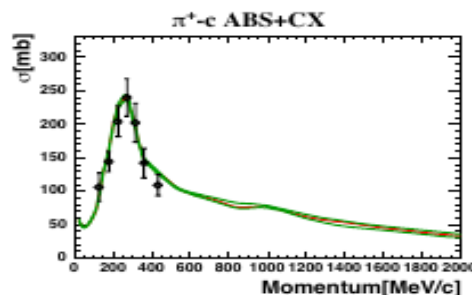
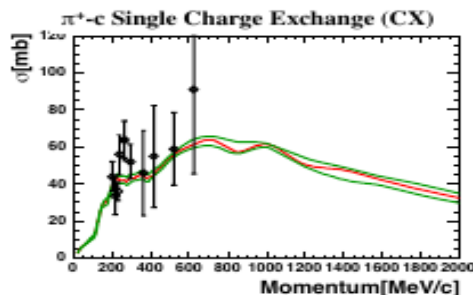
- What uncertainties are we using?
 - Strength of 2p2h is allowed to float within large uncertainties
 - Strength in delta vs non-delta processes will be allowed to vary radically, to ensure we cover the effect in reconstructed neutrino energy (new addition to our model)
 - C/O differences constrained (conservatively) by measurements of SRC in electron scattering
- We don't have 2p2h processes for single pion production in our model (no calculation), but they should certainly be there, with similar effects
 - This will be more important for higher energy experiments, e.g., NOvA and DUNE, than for T2K, HK, SBN

Final State Interactions

- NEUT has its own cascade model
 - Tuned to pion and nucleon scattering on nuclei
 - Data is actually more fairly precise
- Current approach is to use conservative uncertainties because of concern about cascade model itself

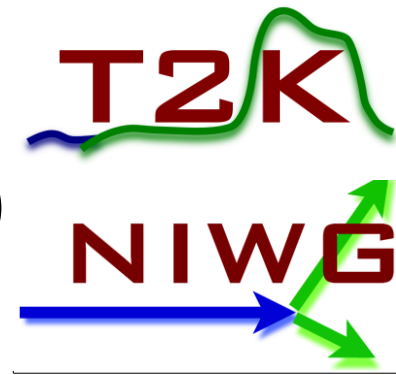


Best fit
 ± 1 sigma
error band

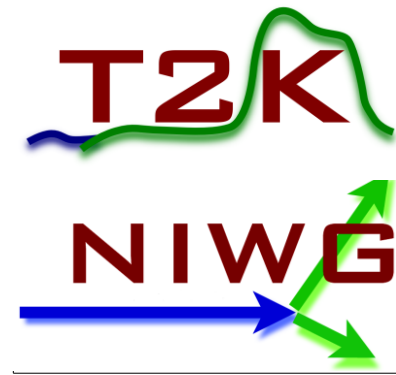


| | $\chi^2_{\min}/N_{\text{DOF}}$ |
|--------------|--------------------------------|
| C | 1.95 |
| O | 3.54 |
| Pb | 2.69 |
| Light nuclei | 2.70 |
| Heavy nuclei | 2.09 |
| All | 2.74 |

Final State Interactions (cont'd)



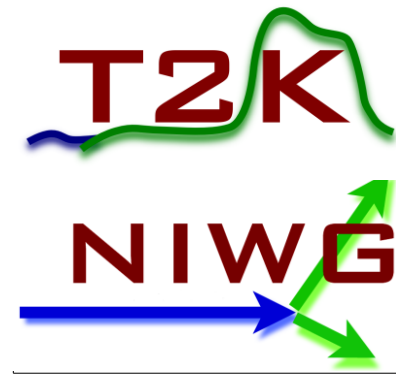
- Current development
 - Use data driven uncertainties, including C/O
 - Incorporate uncertainties on cascade model itself by comparison with transport models (e.g., GiBUU)
- Also working to unify the treatment of FSI uncertainties and secondary interactions (SI) in the detector
 - Both can be done with the same cascade model
- This is a common problem shared by many oscillation experiments



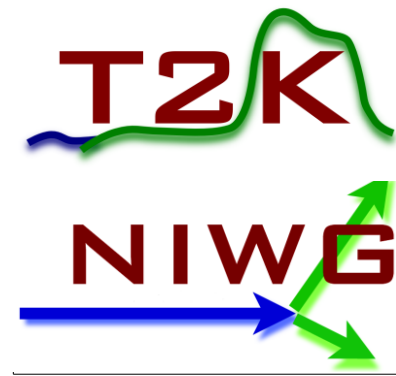
DATA CONSTRAINTS

See, e.g., C. Wilkinson et al., Phys. Rev. D 93, no. 7, 072010 (2016)

Our external data fitting experience

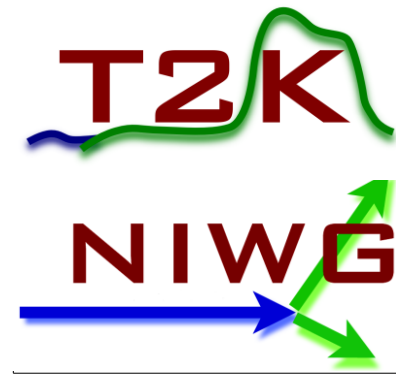


- Successes in fitting deuterium data, MINERvA coherent data, and MINERvA low recoil data
- For CCQE and Pion production on nuclei, have been plagued by disagreements among data sets (within our model)
 - In CCQE, maybe MINERvA low recoil discrepancy is the reason why? In pions, not as clear...
 - So far, reducing uncertainties is hard. But maybe we make the uncertainties more accurate?
- Regardless, better models should help



CONCLUSIONS

Conclusions



- Model is incomplete, inconsistent in places
- Nevertheless, we are able to obtain a reasonable description of our data
 - And external data, at least in part
- Model is significantly more sophisticated than our first in term terms of driving uncertainties from data, theory or discrepancy
- Much development underway that we expect will lead to further improvement or realism